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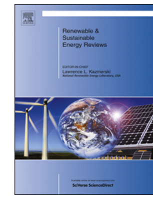

Grid-connected photovoltaic system in Malaysia: A review on voltage issues

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ABSTRACT

Photovoltaic (PV) systems are the most promising renewable energy source in Malaysia due to its abundant solar irradiation. The Malaysian government has launched various renewable energy programs to encourage the use of PV systems. Most of the PV systems are single-phase and the installation is customer driven. Therefore, the growth of PV system in low voltage (LV) distribution network has the potential to raise several technical issues including voltage rise and voltage unbalance. Furthermore, Malaysia is a warm country and geographically surrounded by the sea. The vaporization of the sea water together with the seasonal winds results in a large amount of passing clouds, making this country to be, possibly, the cloudiest region in the world. The solar irradiation is therefore highly scattered and fluctuating. The power output from PV is highly intermittent, hence producing an enormous amount of voltage fluctuations and flickers on the LV distribution networks. All these voltage issues have to be studied experimentally and addressed thoroughly at the early stage before the amount of PV on the network becomes substantial. Therefore, a 7.2 kW grid connected PV system on a radial LV distribution network has been set up to study the voltage issues at the point of common coupling. The power outputs of the PV system are characterised and compared with that of other countries. The probability density of voltage rise and voltage unbalanced factors are derived from the measurement data. Short-term and long-term voltage flicker indexes are calculated to evaluate the severity of the flicker emission. These results are valuable to the policy makers, electricity regulatory body, utility company, customers and PV manufacturers because they can change the policy on the renewable energy and the regulatory framework.

Contents

1. Introduction

Global warming due to the excessive greenhouse gas (GHG) emission has been a concerning issue. Malaysian government is

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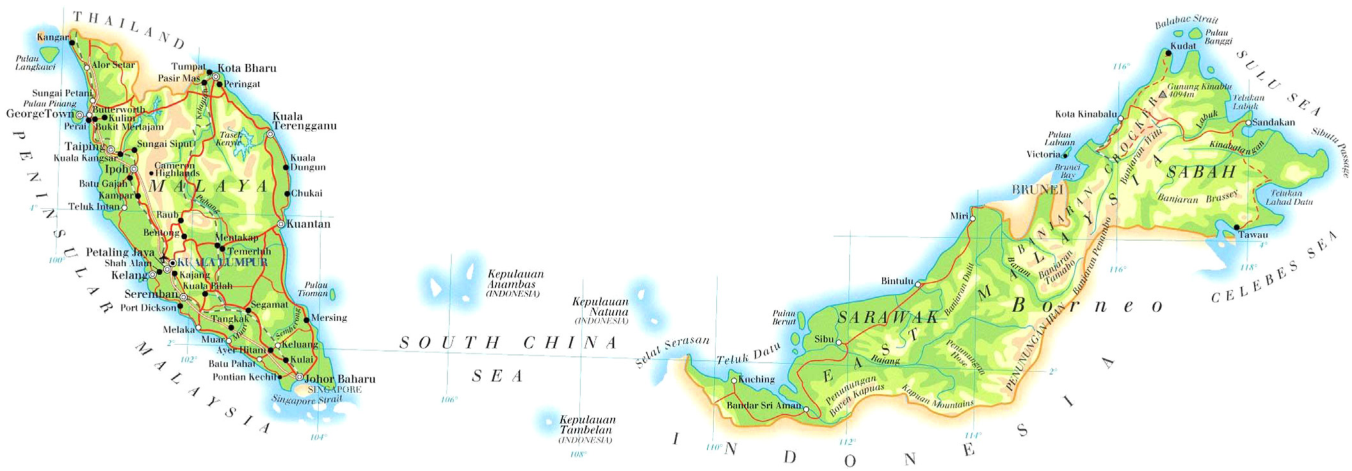

Fig. 1. Map of Malaysia [6].

committed to the reduction of greenhouse gas (GHG) emission by 40% in year 2030 as compared to 2005 level. As a result, the government has launched various programmes to promote renewable energies. Many research papers have been published to discuss the current prospective scenarios for the solar energy development, initiatives and the renewable energy policies in Malaysia.

The authors in [1] present an overview of the current perspective for renewable energy development in Malaysia. There are several potential renewable energy sources available in Malaysia, such as solar, biomass, biogas, mini-hydro, and municipal solid waste. The government has introduced a comprehensive policy in implementing renewable energy. The current installed photovoltaic (PV) capacity is approximately 20 MW [2,3]. It is expected that solar energy has the potential to reach more than 6500 MW by 2030. There is approximately 39 MW in biomass and 4.45 MW in biogas under construction as of July 2009. The potential capacity of both biomass and biogas can become 1340 MW and 410 MW, respectively by 2028. The current mini-hydro generation is approximately 30.3 MW and should reach 490 MW by 2020. As for waste power generation, the total capacity is 5.5 MW in August 2009 and can be 360 MW by 2020. With these continuous efforts, Malaysia can be one of the largest producers in renewable and sustainable energy in the world.

The solar energy outlook has been positive and is expected to surpass all other renewable energy sources in Malaysia by year 2050 [4]. This is because Malaysia is a tropical country as shown in Fig. 1 where high solar irradiance is available throughout the year. The Malaysian government has put in efforts to encourage the utilisation of photovoltaic systems especially to the domestic users. The authors of [5] state that Malaysia is likely to be one of the largest solar power producers in the world in the near future. Various research and development on inverters, PV concentrators, solar cells fabrications and characterization have been carried out by many local research institutions. These include research work on grid-connected inverters, development of solar cells and PV concentrator and PV power systems. These research efforts coupled with the government policy on solar energy can stimulate the PV market growth substantially. The Malaysian government has also introduced solar energy programmes such as Suria 1000, Malaysia Building Integrated Photovoltaic (MBIPV) and Feed-In Tariff (FiT) mechanism.

PV systems are expected to grow very rapid on the low voltage distribution networks and hence create several technical issues on the distribution networks. These technical issues can be voltage rise, voltage unbalance, network power losses, reversed power flow and the thermal limits of transformers being exceeded as described in [7–12].The voltage unbalance can be the most serious technical issue because most of the PV systems are single-phase and connected to the low-voltage distribution networks through “fit and inform” principle by customers [7]. However, the majority of the publications present the results based on simulation modelling in Matlab/Simulink or PSCAD. These virtual analyses are not able to consider many other practical factors, such as the passing clouds over the PV panels.

Malaysia is a tropical country geographically surrounded by the seas. The vaporisation of the sea water together with the seasonal winds results in the large amount passing clouds. Fig. 2 shows the global climatology data of the complete clear sky index around the globe. It is shown that Malaysia has no clear sky all year round as compared to any other countries in the world. Under cloudy sky condition, the solar irradiation is highly scattered and fluctuating, hence making the power output of the PV systems to fluctuate substantially [13]. Hence, the intermittent power output from PV tends to generate an enormous amount of voltage fluctuations and flicker to the LV distribution networks.

The technical issues caused by the PV systems in Malaysia become very unique because they are very dynamic instead of steady state. Experimental studies on voltage issues caused by the PV systems are necessary because only experimental data can show the real quality of voltage. All these voltage issues have to be studied and addressed thoroughly at the early stage before the amount of PV systems becomes substantial on the networks. Hence, the objective of this paper is to present the characteristics of voltage quality on the point of common coupling of the distribution networks with photovoltaic systems in Malaysia.

This paper begins with description of an experimental setup consisting of two PV systems, a network emulator and a monitoring system. Section 3 shows the PV power output characteristics. Section 4 presents the characteristics of the voltage rise, voltage unbalance and the voltage flicker on the network. Sections 5 and 6 provide the discussion on the impacts of the technical issues and the need of regulatory frameworks for PV installation.

2. Experimental network set up

To characterize the PV power output and study the voltage quality at the point of common connection (PCC), a laboratory network system consisting of two 3.6 kWp single-phase PV systems, three-phase loads and a monitoring system has been set up as shown in Fig. 3. Table 1 shows the resistance and

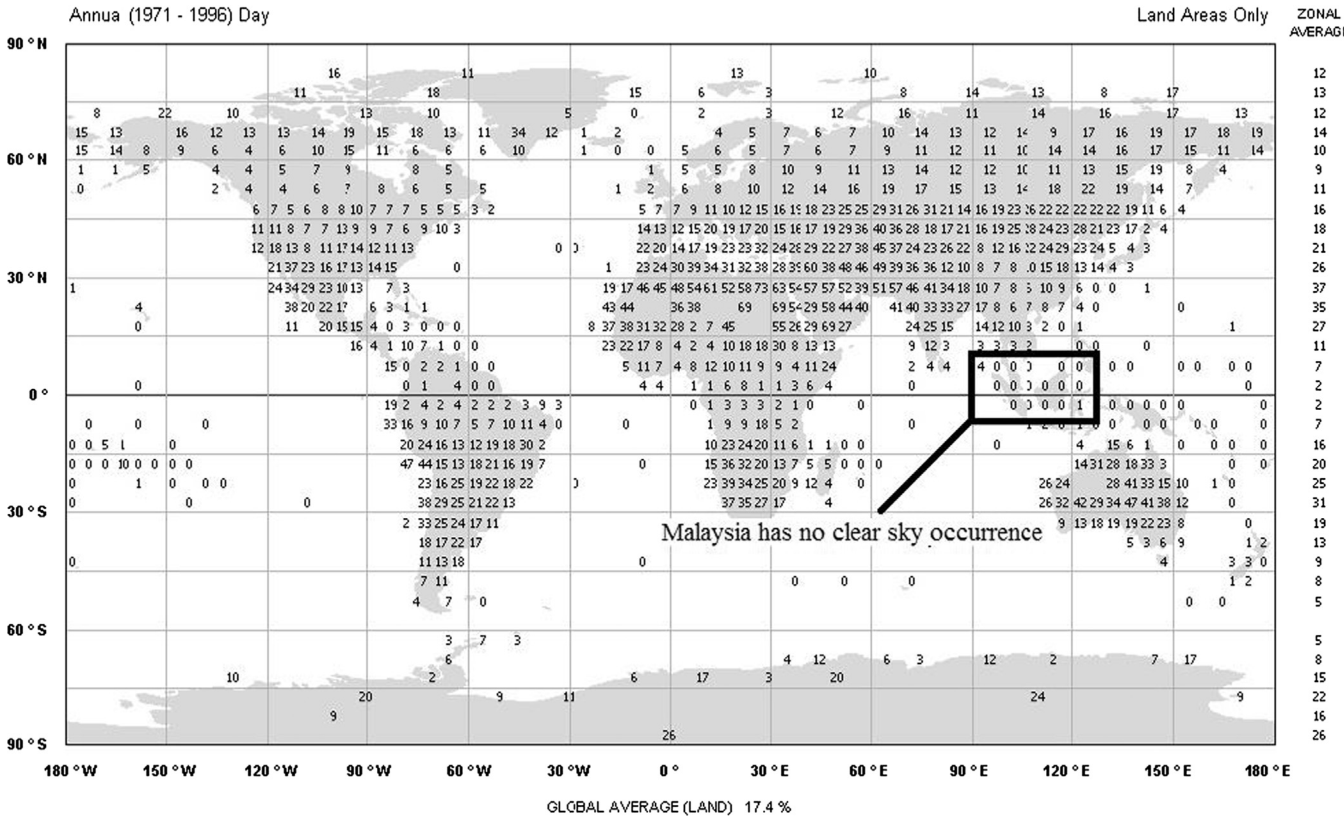

Fig. 2. Frequency occurrence of the global completely clear sky index [14].

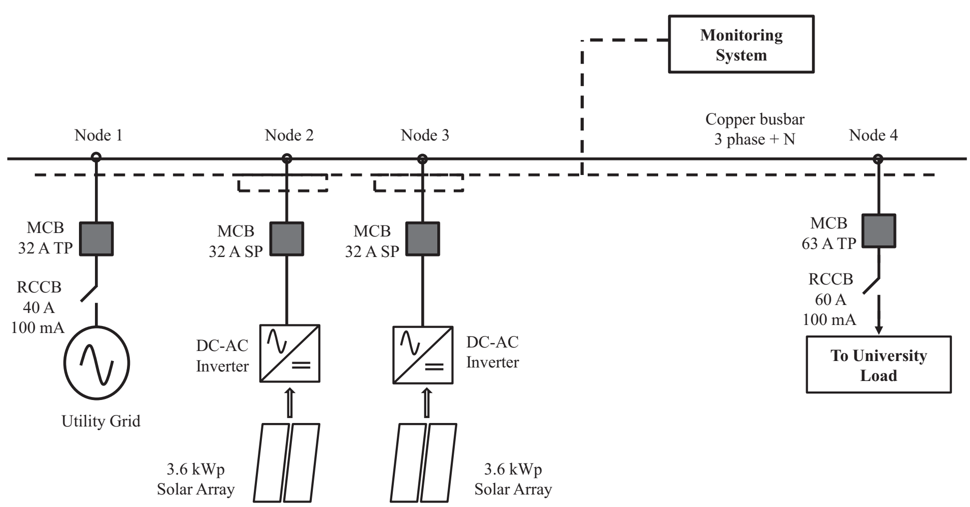

Fig. 3. Line diagram of a three-phase low-voltage distribution network integrated with the two PV systems.

Table 1
Parameters of the cables.

Type of cable	Resistance (at 50 Hz at 90 °C)	Reactance (at 50 Hz)
300MMP 4C XLPE Al	0.13 Ω/km	0.072 Ω/km
70MMP 4C XLPE Al	0.568 Ω/km	0.075 Ω/km

reactance of the existing underground cable. The monitoring system is to measure the three phase voltage and power flow of the PV systems. Miniature circuit breakers (MCB) are installed before each node to protect overload and short circuit current.

Each PV system consists of 16 PV modules and a 3 kW DC–AC inverter. These PV modules are mounted on top of a 3.3 m height metal structure as illustrated in Fig. 4. The PV modules are installed facing north tilt 5°. With this angle, any dust can be washed away by the rains. Each module has a maximum capacity of 230 W, hence making up a total of 3.6 kWp. A monitoring system is used to monitor the performance of the PV power output and the voltage magnitude at the PCC. The monitoring system consists of a supervisory computer integrated with national instrument (NI) data acquisition chassis, NI9225 voltage module and NI9227 current module. LabVIEW is used as a programming platform to log the required three-phase voltage and power into the supervisory PC.

These PV modules are commercially available products that comply with all the technical standards. Table 2 shows the technical specification of the PV panel.

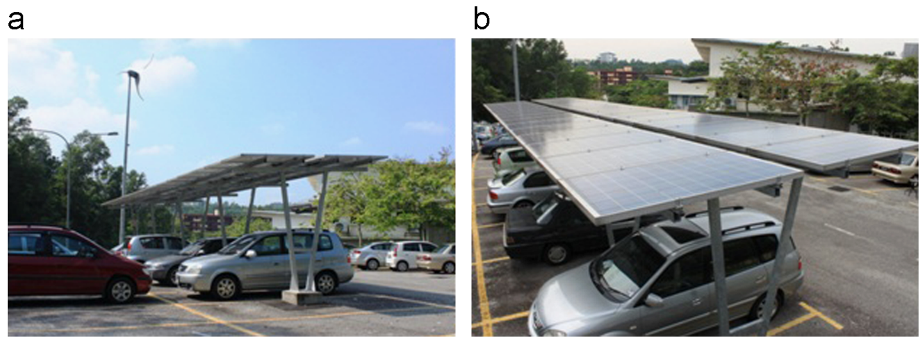

Fig. 4. PV modules are mounted on a 3.3 m height metal structure at the University car park area. (a) Bottom view of PV panels and (b) Top view of PV panels.

Table 2
Technical specification of PV module.

No	Characteristics	Specifications
1	Maximum power (P_{max})	230 W
2	Short circuit current (I_{sc})	8.42 A
3	Open circuit voltage (V_{ac})	37 V
4	Maximum power current (I_{pmax})	7.83 A
5	Maximum power voltage (V_{pmax})	29.4 V
6	Maximum system open circuit voltage	1000 V

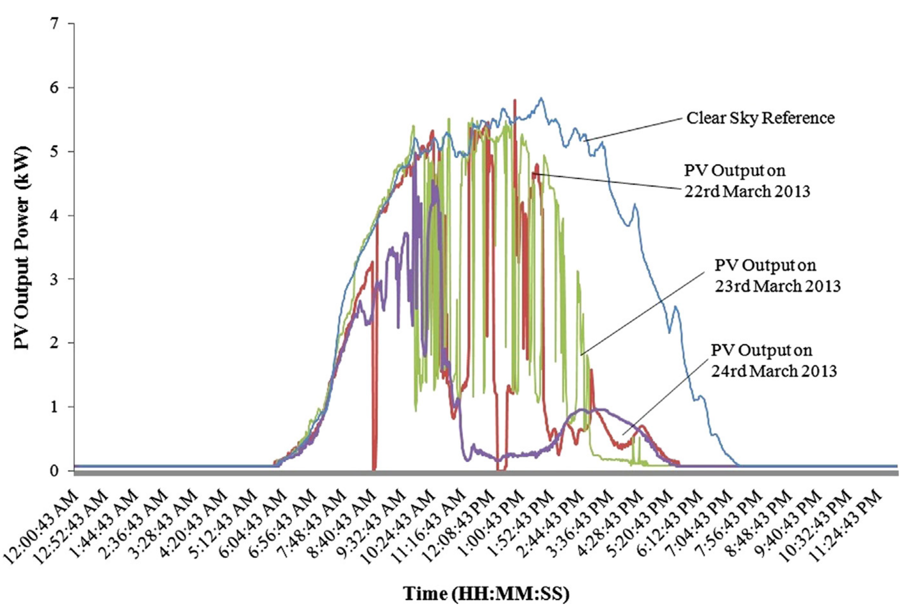

Fig. 5. PV power output of three random days as compared to a clear sky reference.

3. Characterization of photovoltaic power output

Malaysia is on the equatorial region that has a high irradiance level all year round. The level of irradiance in Malaysia is in the range of 1470 kW h/m^2/year to 1700 kW h/m^2/year [15]. One of the 3.6 kW PV systems is monitored over 9 months. Fig. 5 shows the PV power outputs on 22nd, 23rd and 24th March 2013. Fig. 6 shows the some of the daily yields. It is shown that the power outputs fluctuate frequently throughout the days as compared to that of a clear sky reference. This reference values is the maximum PV power output at that particular period. The numerous fluctuation of the power outputs are caused by the high frequency of the passing clouds over the PV systems. It is also noticed that many of the high power output drop suddenly rather than gradually. This is because many of the passing clouds are very thick, hence causing a sudden reduction in the total solar irradiation.

The PV power outputs are characterized to show the frequency of the power outputs and the corresponding durations as shown in Fig. 7. The chart shows the majority of the PV power outputs are within the range of 1.5 kW and 3.0 kW. It is also noticed that the majority of the PV power output happens within the duration of less than 5 min.

A comprehensive PV data from China, Hong Kong, London and Thailand are obtained from the sources [16–18] in order to derive the PV output characteristics as shown in Fig. 8. It is shown that the majority of the PV power outputs in China, Hong Kong and UK happen within the duration of more than 30 min which is much longer than that in Malaysia. However, it is noticed that the lifespan of some high PV power outputs in Thailand are short, less than 5 min. This is because Thailand is close to Malaysia, making this region vulnerable to much passing clouds.

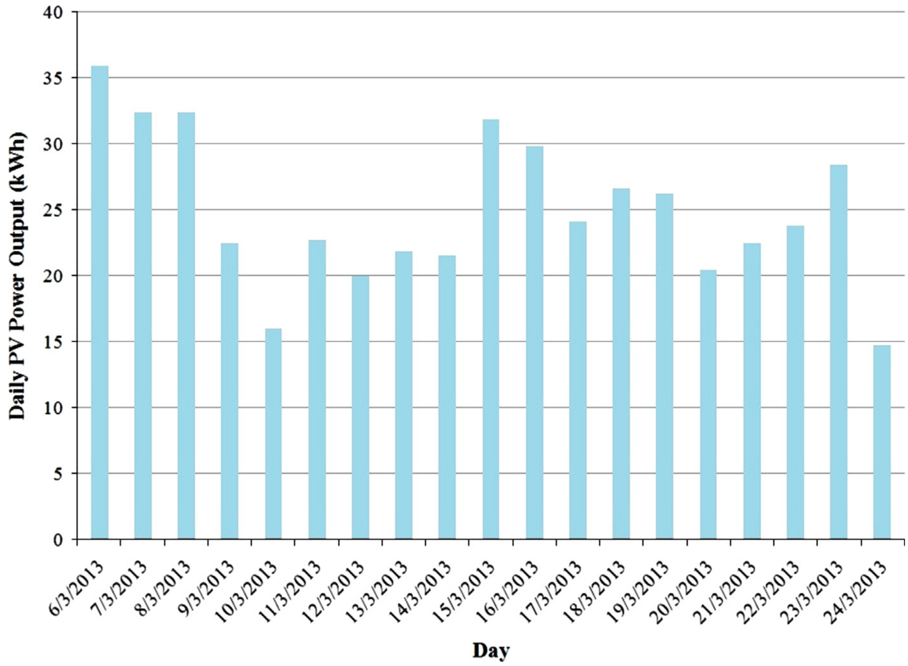

Fig. 6. Daily PV power output in kW h.

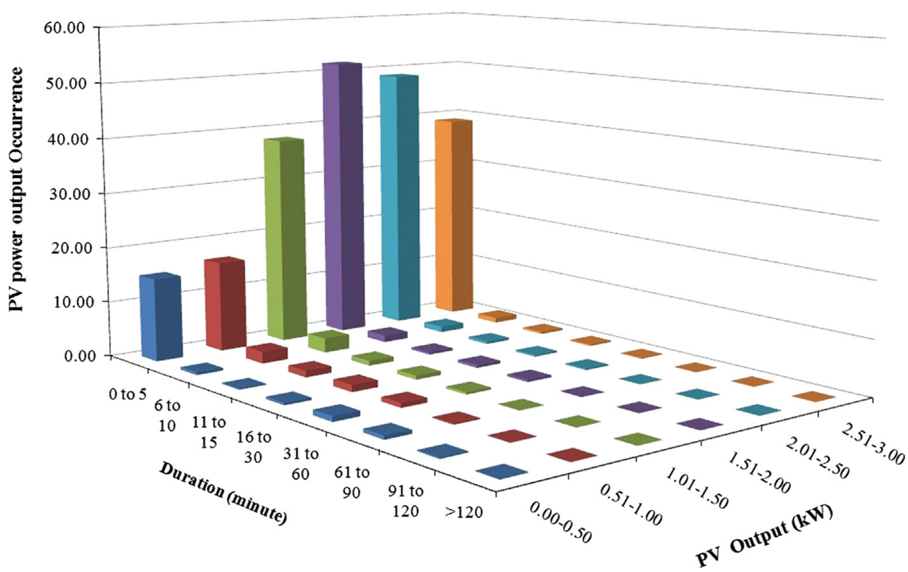

Fig. 7. Characteristic of the PV power output in Kuala Lumpur, Malaysia.

4. Voltage quality issues caused by the intermittency of PV power output

Voltage at the point of the common coupling (PCC) are monitored over a period of 9 months and then characterized to show the probabilistic occurrence of voltage rises, voltage unbalance and flickers on the network.

4.1. Characteristic of voltage rises

The PV systems are installed at Phase C. The three-phase voltage at the PCC is recorded on a regular basis. The probability counts of different voltage levels on phase A–C at the PCC are determined as shown in Fig. 9. The probability counts for having the voltage levels within the range of 247 V and 248 V are the highest on Phases A and B. The probability counts for having voltage within the range of 249 V to 250 V are the highest on Phase C. There are some voltage magnitudes happening within the range of 251 V to 252 V which is at the border of the statutory limits. Furthermore, there are several voltage magnitudes being greater than 252 V which is beyond the statutory limits.

In this study, the upper voltage limit is set at 249 V. The probability of having voltage being greater than 249 V within a day is determined so that the likelihood of having voltage violation per day can be defined. Fig. 10 shows the daily kW h generated by the PV system and the probability of having violation per day on Phase C. It is shown that the probability of having voltage violation per day is about 47% on average. It is clearly illustrated that the violation of voltage rise is very apparent in the low voltage distribution networks in Malaysia.

4.2. Characteristic of voltage unbalance

Majority of the PV systems are single phase and the growth of the PV systems are driven by customers and not centrally planned. Therefore, the voltage unbalanced at the PCC is likely to increase

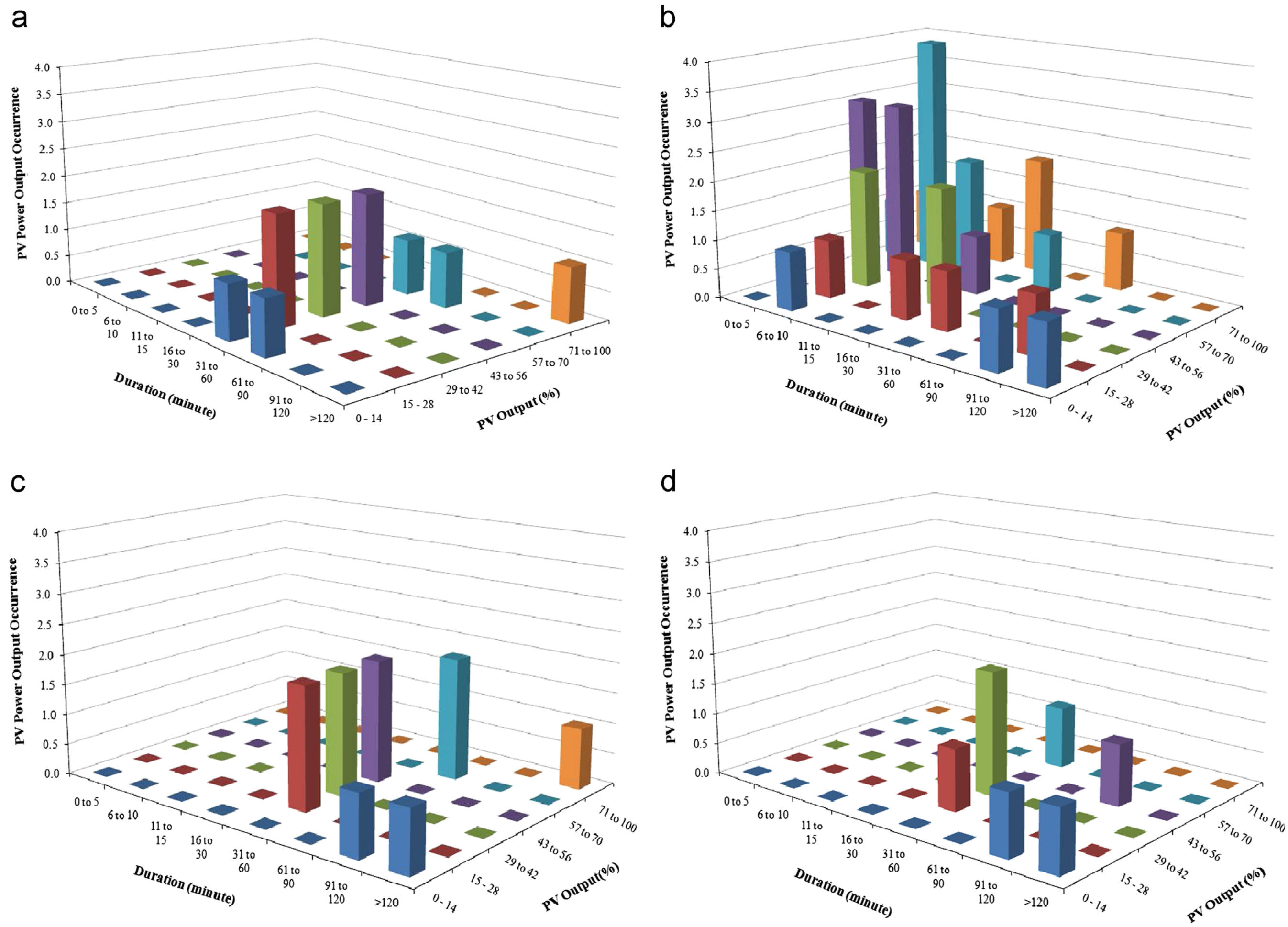

Fig. 8. Characteristic of the PV power output for Thailand, China, Hong Kong and UK. (a) China, (b) Thailand, (c) London and (d) Hong Kong.

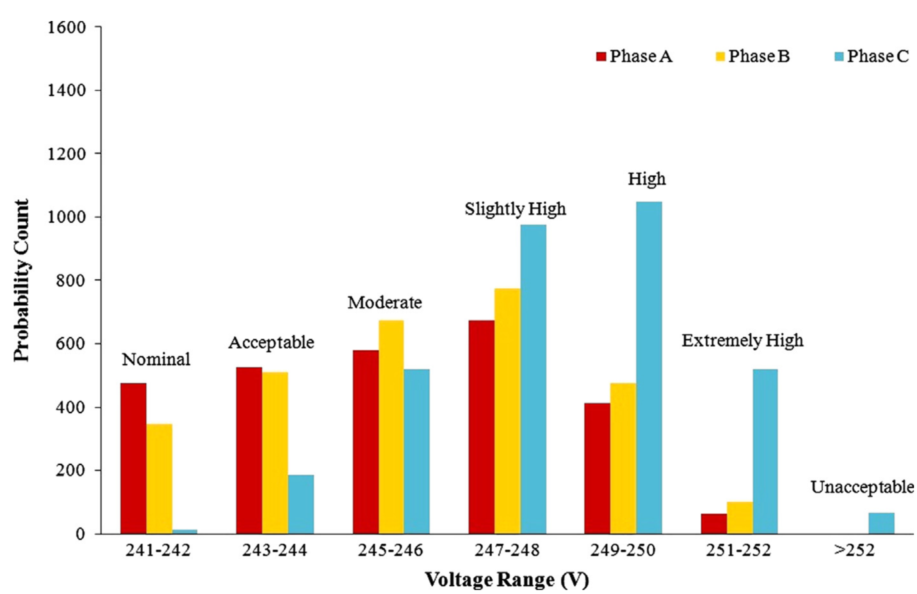

Fig. 9. Probability counts of different voltage levels encountered at PCC.

with the growth of PV systems on the LV networks. Voltage unbalanced factor (VUF) is used to evaluate the degree of unbalance [19]. It is defined as follows:-

$$\mathrm{VUF}(\%) = \frac{V^-}{V^+} \times 100\% \tag{1}$$

where VUF is the voltage unbalance factor; V^- is the negative sequence voltage; and V^+ is the positive sequence voltage.

The acceptable tolerance of the voltage unbalance factor is 2% in Malaysia. Fig. 11 shows the relationship between the PV power output and the VUF on the 15th March 2012. The network VUF is approximately 0.5% when there is minimum PV power output

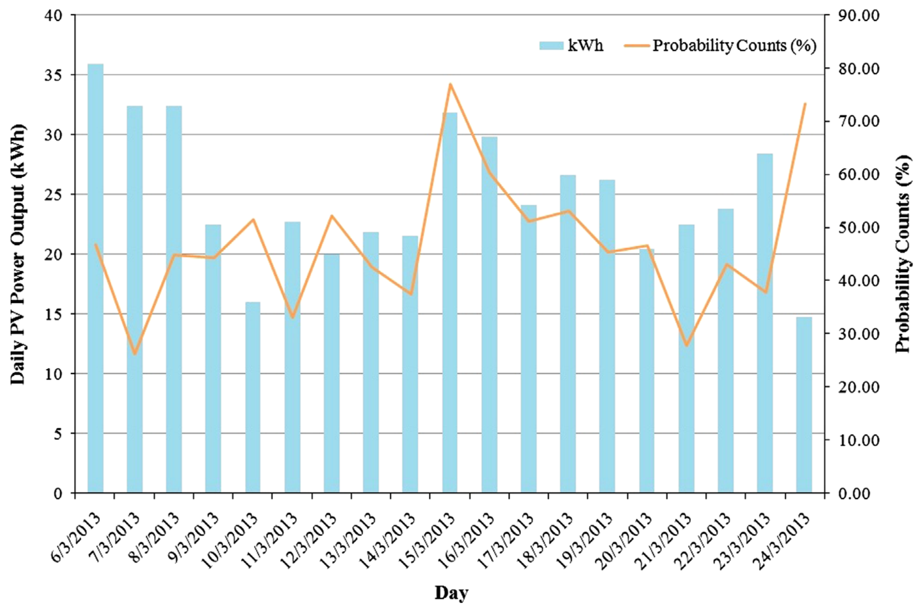

Fig. 10. Probability counts for the voltage rise and the PV power output in kW h.

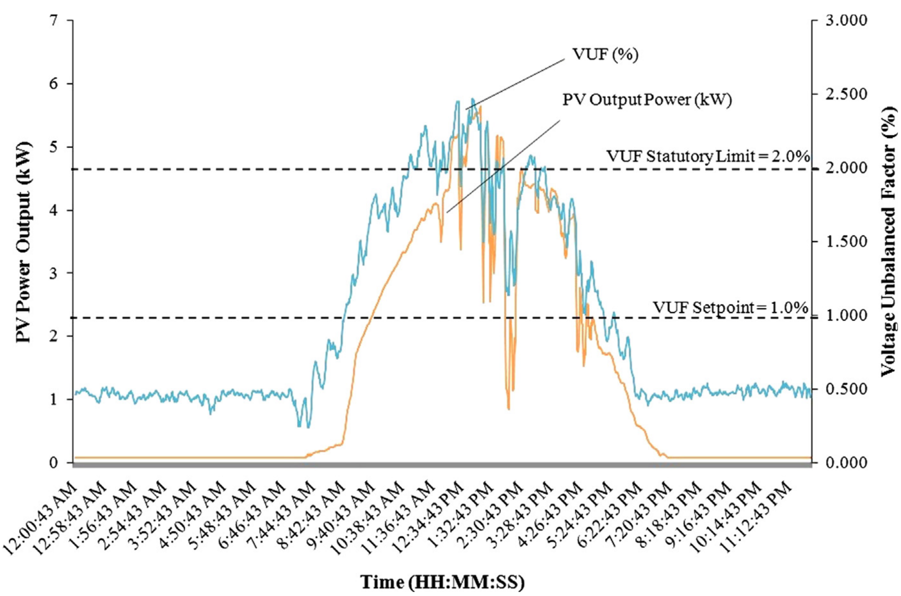

Fig. 11. Relationship between the VUF and the PV power output on the 15th March 2013.

from 12.00 am to 8.00 am. The VUF increases together with the PV power output. The VUF at the PCC hits beyond the acceptable tolerance of 2% during the peak PV power output which happen from 12.00 pm to 2.00 pm of the day. Eventually, the VUF drops to the minimum level when there is little PV power output starting from 6.30 pm.

A probability chart is plotted to show the probability of different VUF throughout the monitoring period. Fig. 12 shows that the majority of the VUF happens between 1% to 2% and the corresponding durations are 60 s. However, it is also shown that the violation of VUF occurs and duration is more than 60 s. Such violation is not acceptable by the utility companies. It is shown clearly that the violation of VUF can happens in Malaysia.

4.3. Quantification of voltage fluctuation and flicker

The severity of flicker can be defined by calculating the short-term and long-term flicker indices. The short-term flicker index is calculated by integrating the voltage fluctuations over the period of 10 min, while the long-term flicker index is defined by integrating the voltage fluctuations over 2 h.

The PV systems generate power from 8.00 am to 6.00 pm. Therefore, the collection of voltage magnitude within this period is used to calculate the short-term and long-term flickers. Fig. 13 shows the short-term and long-term flicker indices at Phase C where the PVs are connected. The statutory limits for both the short-term and long-term flicker indices are 1.0 and 0.65, respectively. It is shown that the short-term flicker indices always rise above the maximum limit of 1.0. The long-term flickers will rise above the limit of 0.65 at 65% of the time. It is also noticed that when there is minimum PV output, the short-term flicker index is 0.38 while the long-term flicker index is 0.36. These values represent the background flicker indices and they are very much depending on the activities on the premise. It is clearly proved that the flickers on the network integrated with PV systems are very severe under the high frequency of the passing clouds.

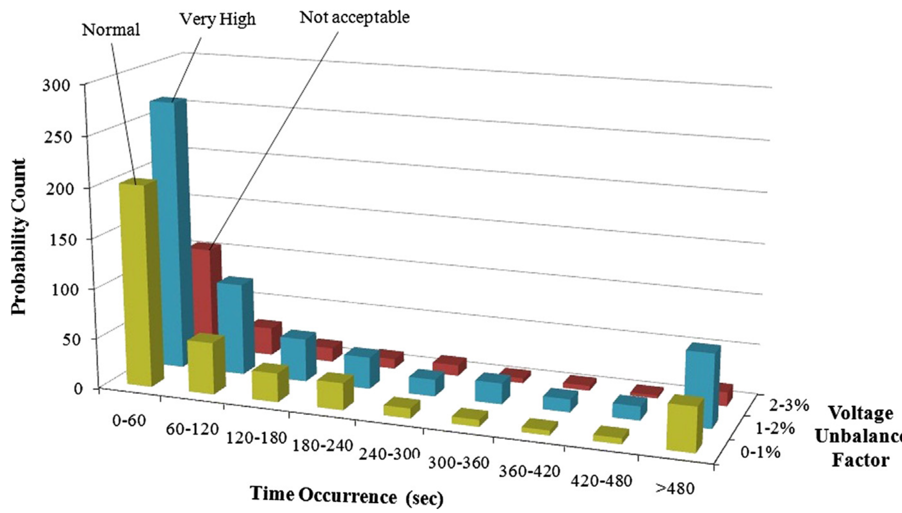

Fig. 12. Probability counts of the voltage unbalance factor with respect to different time period.

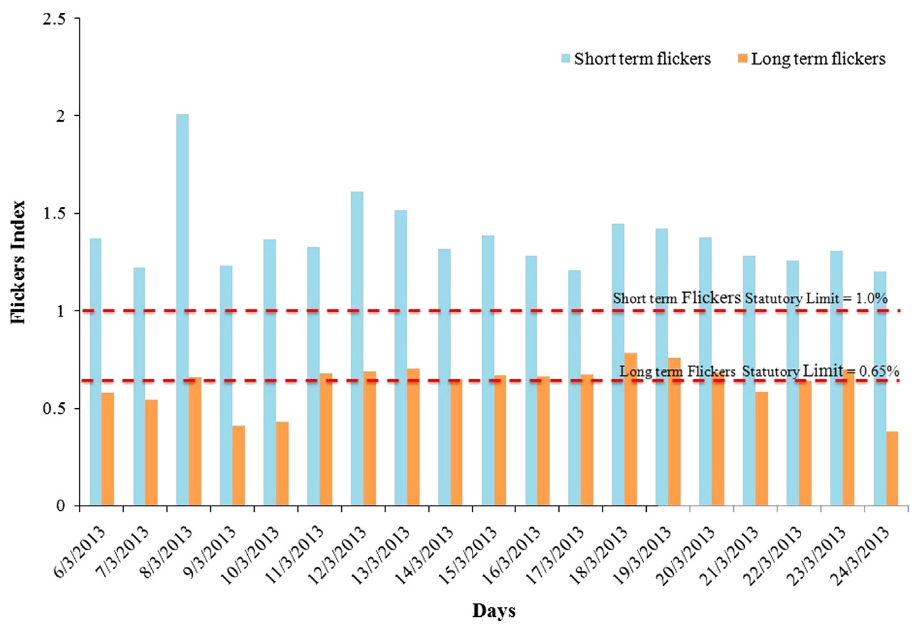

Fig. 13. Short-term flicker and long-term flicker indices at the point of connection with the PV systems.

5. Impacts of voltage issues on the LV distribution networks

According to the MS IEC (Malaysian International Electrotechnical Commission) standard, the statutory tolerance for voltage excursion on the LV distribution network is +10% and −6% with the reference to the 230 V [20]. Unwanted voltage rise in the network can caused damage to the household equipments. In a three-phase network, voltage unbalance takes place when the magnitude of each phase voltage is different or the phase angle between any two phase voltages differs from the balanced conditions. The fundamental principles of a three-phase four wire systems show that there should be a small degree of the three-phase voltage unbalance if a balanced load condition is to be maintained. However, such a situation is hardly achieved because of the use of single-phase and non-linear loads such as switch-mode power supplies. A voltage unbalance of 1% can create 6 to 10 times the current unbalance. This current unbalance can create unnecessary temperature rise in the motor windings that degrade the performance and shorten the lifespan of the induction motors. The unbalanced condition could also be deteriorated if a large amount of single-phase renewable energy sources are installed on the distribution networks [21].

Voltage fluctuation and flicker are commonly happened on the high voltage (HV) and medium voltage (MV) networks [22]. This is because arc furnace, welding machines, rolling mills and mine winders are mainly connected to the HV and MV networks [23]. However, flickers are not common on the LV networks. If they happen on the LV networks, their durations are usually very short. This is because the LV flickers are caused by the starting of large electrical motors, X-ray, pumps and refrigerators [24]. The impacts are not significant. However, if the occurrence of the flickers is too frequent, then electrical motors can change in their starting torques and increase their power consumptions, hence creating additional heats and so reducing the efficiency of the machines. This can shorten the lifespan of the motors. Voltage fluctuation and flicker can cause light sources to vary their luminous. Individual who is affected by light flickers may suffer from headaches, migraines and eye discomfort. In addition, unstable voltage supply causes electronic equipment malfunction, unwanted

Table 3
Feed-in-tariff (FiT) rate for solar in Malaysia [29].

No	Descriptions	Feed-in tariff rate (MYR/kW h)	Feed-in tariff rate*(USD/kW h)
(a)	Solar photovoltaic installation with capacity of:		
i	Up to and including 4 kW	1.23	0.41
ii	Above 4 kW, up to and including 24 kW	1.20	0.40
iii	Above 24 kW, up to and including 72 kW	1.18	0.39
iv	Above 72 kW, up to and including 1 MW	1.14	0.38
v	Above 1 MW, up to and including 10 MW	0.95	0.32
vi	Above 10 MW, up to and including 30 MW	0.85	0.28
(b)	Solar photovoltaic installation (a) with criteria as follows entitle to have additional bonus:		
i	Use as installations in buildings or building structure	+0.26	+0.09
ii	Use as buildings materials	+0.25	+0.08
iii	Use of locally manufactured or assembled solar photovoltaic modules	+0.03	+0.01
iv	Use of locally manufactured or assembled solar inverters	+0.01	+0.003

* Feed-in Tariff rate in US Dollar (USD)/kW h are converted based on a conversion rate of USD 1.00=MYR 3.00.

triggering of uninterruptable power supply (UPS) units to switch to battery mode and reduce the operational efficiency [25].

6. The need of the regulatory frameworks of the technical issues caused by the PV systems

The Malaysian government has developed key policies and strategic to achieve the nation's policy in which to mitigate the issues of security, energy efficiency and environmental impact for over 30 years [26]. Recently, the Malaysian government has aggressively put in enormous initiatives and efforts to promote renewable energy (RE) utilization. In the 10th Malaysian Plan, the government has targeted to achieve 985 MW by 2015, contributing to 5.5% of Malaysian's total electricity generation mix [27]. Of all the policies, the Malaysian government has introduced Feed-in Tariff (FiT) to foster RE because it has successfully implemented in over 40 countries including Germany, Spain, Italy and Thailand. FiTs are payments for those who generate electricity with RE sources. Table 3 shows the details of feed-in tariff rate for solar in Malaysia. Under RE fund by Pusat Tenaga Malaysia (PTM), consumers who utilize electricity more than the minimum point must contribute 1% of their bill towards the fund. These funds will be used to equalize between the renewable and non-renewable sources [28].

Table 3 Feed-in-tariff (FiT) rate for solar in Malaysia [9]. Photovoltaic system, being one of the most promising RE sources in Malaysia, has the possibility to grow tremendously on the public LV distribution networks. Grid connected PV has an average annual growth of 81%, mainly driven by the FiT [30]. Although the Malaysian government has developed an effective policy on renewable energy to reduce the dependency of fossil fuel and mitigate the effect of climate change, none of these policies provided a detailed guideline on the installations of PV systems. The technical issues are apparent in Malaysia where the frequency of passing clouds is possibly the highest in the world.

Government and the utility company should establish the financial support scheme to enhance and mitigate the power quality issues caused by the photovoltaic systems. The funding can be creating from the electricity bills, tax revenue, or a combination of both. The Malaysian government can imitate the FiT funding policy by including all system added cost for power quality mitigation system to the rate base and share among all electricity customers. However, the drawback of this option by spreading the cost may burden the society in large. The government can also allocate the tax revenue to implement the system. There is also alternative approach to impose specific tax such as energy tax or carbon tax. Funding generated from the tax has the possible risks because the stability of the policy environment can change with political and budgetary priorities.

National Renewable Energy Laboratory (NREL) also suggests that this funding can be also generated through inter-utility cost sharing. Utility companies operate under high solar power district do not shoulder the full burden of any supplementary costs [31]. However, Malaysian electricity is a regulated market, the only utility company and the system operator in the Peninsula Malaysia is Tenaga Nasional Berhad (TNB), while the only company supplying electricity in Sabah and Sarawak is Sabah Electricity Sdn Bhd (SESB) and Sarawak Electricity Supply Corporation (SESCO), respectively. The electricity market in Malaysia is very different from the deregulated market in the United States, United Kingdom and Singapore. Therefore, there is no inter-utility cost sharing as the utility companies in Malaysia monopolize the electricity market in the Peninsula Malaysia, Sabah and Sarawak. Of the entire funding scheme proposed as the above, it is very likely Malaysian government opt for the ratepayer or taxpayer.

7. Feasible methods for voltage stabilization

Renewable curtailment is the usual approach used to ensure that the voltage is within the acceptable limits [32]. However, this method is not recommended as it limits the reduction of carbon footprint and reduces the revenue of the owners of the renewable energy sources. As a result, several research papers have proposed solutions to mitigate the power quality issues caused by the high penetration of PV on the LV distribution networks. Among these solutions, super-capacitor is proposed to mitigate the voltage flickers caused by the intermittent PV power output [33]. Static synchronous compensator (STATCOM) integrated with an energy storage system is proposed to stabilize the system voltage and to provide active power support during the grid contingency [34]. Authors in [35] have developed an active management solution that coordinates the control of on-load-tap-changer (OLTC) and the installed reactive power compensator. All these methods maintain the voltage magnitude at the point of concern by manipulating the flow of reactive power between the networks and the compensator. However, the voltage control using reactive power is not as effective as using real power because the distribution network has a greater resistance than reactance.

Energy storage system emerges to be an effective approach for mitigating the voltage issues without curtailing any renewable energy. A numbers of research papers propose the use of the energy storage system to accommodate a large amount of wind energy [36,37]. However, most of the existing energy storage systems are not catered to solve the voltage rise and voltage

unbalance issues that fluctuate throughout the day on the distribution network. Therefore, an effective control strategy is needed for the energy storage systems to mitigate the fluctuating voltage rise and voltage unbalance on the distribution networks with photovoltaic systems. Therefore, a research project is being carried out to develop a fuzzy control algorithm for the energy storage system consisting a bi-directional inverter and lead-acid batteries. The fuzzy controlled energy storage system is able to mitigate the fluctuating voltage rises and voltage unbalances on the network by actively manipulating the active power flow between the energy storage system and the low-voltage distribution network. The fuzzy control system instructs the bi-directional inverter to carry the necessary pre-emptive action before the voltage excursion becomes too significant. Such action is to ensure the voltage level and voltage unbalances are restored as soon as possible before it is out of order.

8. Conclusion

Photovoltaic systems are likely to become dominant type of the renewable energy sources in the Malaysian market due to its abundant solar irradiance. However, the installation of PV system is driven by customers and non-centrally planned. Therefore, improper coordination on the PV system installation may cause voltage unbalance due to non-uniform distribution. During low load condition, excess power injection may cause voltage rise. To investigate the voltage severity, a 7.2 kWp PV system is connected to the laboratory distribution network. The voltage magnitude have been measured and recorded on a regular basis over a period of time. Throughout the monitoring period, as long as the single phase PV power output is greater than 4 kW, the voltage at PCC is likely to violate its statutory limit. Furthermore, Malaysia is one of the countries with completely zero clear sky. The passing clouds can cause the PV power output to fluctuate frequently throughout the day. The substantial fluctuation of PV power output can cause the magnitude to vary, generating a large amount of flickers to customers. The study has proven that the intermittent PV power output can introduced a maximum short term flickers of 2.0 and long term flickers of 0.78.

Appendix

The following formulas are used to calculate the short-term and long-term flicker indices [25,38].

$$d = \frac{V_{\max} - V_{\min}}{V_{\text{nom}}} \tag{2}$$

where $V_{\max}$ is the maximum voltage; $V_{\min}$ is the minimum voltage and V_{nom} is the nominal voltage.

$$P_{ST} = P_{ST0} \times \frac{d}{d_0} \tag{3}$$

where P_{ST} is the short term flicker; P_{ST0} is the relative short term flicker; d is the voltage change and d_0 is the relative voltage change.

The long-term flicker is also known as the average of the short term flicker. It can be calculated as follows:

$$P_{LT} = \sqrt[3]{\sum_{i=1}^{N} \frac{(P_{ST}^{i})^3}{N}} \tag{4}$$

where N is the total number of short-term flicker within the 2 h and P_{ST}^{i} is the short-term flicker at the number of i.

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